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Chromatic and Luminance Systems Deficits in Glaucoma

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The purpose of this study was to compare the effects of glaucoma, at different stages of the disease process, on the two color-opponent systems and on the luminance system. Discrimination thresholds were measured along the two equiluminant cardinal color axes (RG and YV) and along an achromatic luminance axis (LD) in 27 patients with open-angle glaucoma (OAG) and in 13 glaucoma suspects. Patients with OAG showed increased thresholds along all three axes. The threshold increases correlated significantly with the level of visual field loss. For glaucoma suspects, thresholds were also increased along all three axes. A subgroup of patients with OAG, those with pigmentary glaucoma, showed minimal increases in threshold along the RG axis. To further investigate this finding an additional 15 patients, seven with primary OAG and eight with pigmentary glaucoma were run in a two-alternative forced-choice experiment. For patients with pigmentary glaucoma, thresholds were increased less along the RG axis. The results of the study for OAG patients and glaucoma suspects are consistent with deficits in the two color-opponent systems, and in the luminance system.

Glaucoma Colour opponent systems Psychophysics Discrimination thresholds

Many studies have demonstrated that the short-wavelength-sensitive cone system (S-cone system) is affected by glaucoma. For example, sensitivity to short wavelength light is reported to be selectively reduced not only in patients with glaucoma, but even in glaucoma suspects, prior to the detection of any glaucomatous visual field changes using standard perimetric techniques (e.g. Adams, Rodic, Husted & Stamper, 1982b; Zwas, Shin & McKinnon, 1984; Heron, Adams & Husted, 1988). This type of finding has lead investigators to concentrate on the examination of S-cone system sensitivity in patients with glaucoma, and on the development of techniques for measuring S-cone system sensitivity losses in a clinical setting (e.g. Gündüz, Arden, Perry, Weinstein & Hitchings, 1988; Adams, Heron & Husted, 1987; Johnson, Adams & Lewis, 1989; Hart, Silverman, Trick, Nesher & Gordon, 1990; Sample & Weinreb, 1990; Yu, Falco-Reis, Spileers & Arden, 1991). Few studies have compared the effects of different stages and/or types of open-angle glaucoma (OAG) on the sensitivity of the three cone mechanisms or on the color-opponent and luminance systems (Greenstein, Halevy, Ritch & Zaidi, 1993a; Greenstein, Shapiro, Hood & Zaidi, 1993b; Felius, van den Berg & Spekreijse, 1995). In a preliminary study that included a small group of patients with OAG, we compared sensitivities of S- and M- (middle-wavelength sensitive) pathways to measures of color-opponent and luminance system sensitivities (Greenstein *et al.*, 1993b). Our results indicated that sensitivity losses for the S-cone system were accompanied by significant decreases in the sensitivity of the L–M opponent system and by decreased sensitivity to achromatic contrast.

The purpose of the present study was to confirm our preliminary findings on the sensitivities of the color-opponent and achromatic systems on a larger group of patients with OAG, and to assess the effects of OAG at different stages of the disease process. In particular, we wanted to determine if the S-cone system was selectively affected during the early stages of the disease process, and whether the underlying mechanisms of sensitivity loss differed in different types of glaucoma. Yamazaki, Lakowski and Drance (1989), for example, reported that a group of patients with high-tension glaucoma showed significantly greater sensitivity losses to short-wavelength lights compared to a group with low-tension glaucoma. It is important to establish whether clinical psychophysical tests designed to detect early

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TABLE 1. Clinical characteristics of patients with OAG

Subject	Age (yr)	Acuity	Visual field	Refractive error	Optic disk	Diagnosis
1*7	28	20/20	1	Plano	D	P G
2*7	50	20/20	2	−1.00	D	POAG
3*1	29	20/30−2	5	−5.75 + 1.75 × 85	D	POAG
4*4	37	20/25	3	−6.50 + 2.75 × 90	F	POAG
5*2	38	20/20−1	4	−5.25	M	POAG
6	53	20/25−2	4	−5.25 + 3.50 × 60	M	POAG
7	56	20/20	2	−1.00	D	PXEGL
8	57	20/25	2	−6.50 + 1.25 × 75	D	OAG
9	62	20/15	5	Plano	M	POAG
10	64	20/25	4	−6.50 + 1.25 × 13	F	POAG
11	65	20/20−2	2	Plano	D	POAG
12	68	20/20	2	Plano	F	POAG
13	70	20/20	3	3.25 + 1.25 × 176	D	PXEGL
14*4	34	20/30	4	−6.50	M	PG
15*2	38	20/20	4	−2.25	M	PG
16*3	40	20/25	4	−3.00	D	PG
17*5	43	20/25−2	3	−7.50 + 1.0 × 119	M	PG
18*5	40	20/20	2	−2.50 + 0.50 × 180	F	POAG
19*1	45	20/30	5	−8.25 + 0.75 × 155	M	PG
20	53	20/20−2	1	−4.25 + 1.00 × 62	M	POAG
21*6	45	20/30	2	−10.0 + 0.50 × 100	D	POAG
22	67	20/20	2	+0.50 + 1.00 × 180	F	POAG
23	64	20/25	2	−4.75 + 1.00 × 140	M	PXEGLS
24*3	45	20/20	2	−0.75 + 1.00 × 80	M	POAG
25*6	47	20/20	2	−1.75	D	PG
26	41	20/20	3	Plano −0.50 × 35	F	POAG
27	70	20/20−1	3	−4.00 + 1.25 × 178	F	LTG

POAG, primary open-angle glaucoma; PG, pigmentary glaucoma; PXEGL, pseudoexfoliative glaucoma; LTG, low tension glaucoma.

Visual field loss: 1, relative scotoma >6 deg from fixation in one hemifield; 2, relative scotoma in both superior and inferior hemifields; 3, arcuate scotoma in one hemifield, or scotoma ≤6 deg from fixation, or absolute scotoma; 4, arcuate scotoma in one hemifield and relative scotoma in other hemifield; 5, arcuate scotoma in both superior and inferior hemifields.

Optic disk evaluation: D, diffuse; F, focal; M, mixed retinal nerve fiber damage.

*Patients selected for comparative study of effects of PG vs POAG.

glaucomatous damage in "primary open-angle" glaucoma (POAG) suspects are equally effective for monitoring disease progression in patients with established OAG, or with other types of glaucoma.

We assumed that the first stage of the visual system comprises three independent cone mechanisms, the L-, M-, and S-cone mechanisms, and the second stage two independent chromatic mechanisms and one achromatic mechanism. The spectral sensitivities of the cones were assumed to correspond to the Smith and Pokorny fundamentals (Smith & Pokorny, 1975), and the mechanisms of the second stage to those identified by the cardinal directions experiment of Krauskopf, Williams and Heeley (1982). In this study the sensitivities of the two opponent color systems were evaluated in patients with OAG and in glaucoma suspects by measuring thresholds along two equiluminant axes, a YV and a RG axis. Sensitivity to achromatic luminance contrast was evaluated by measuring thresholds along an achromatic axis.

EXPERIMENT 1

Methods

Observers. Three groups of observers participated in this part of the study: 13 glaucoma suspects (mean age = 45.5 yr; SD = 14 yr; range = 16–64 yr), 27 patients with OAG (mean age = 50 yr; SD = 12.9 yr; range = 29–70 yr) and 25 age-similar normal observers (mean age = 44.1 yr; SD = 13 yr; range = 24–70 yr). The patients with OAG and the glaucoma suspects were referred from the Glaucoma Clinic at New York Eye and Ear Infirmary. The term glaucoma suspect was applied to patients with intra-ocular pressures (IOP) ≥ 22 mm Hg on two or more occasions but who showed no evidence of glaucomatous cupping or visual field defects. Patients with OAG had glaucomatous cupping and varying degrees of visual field loss. Table 1 summarizes the clinical characteristics and diagnoses of the 27 patients with OAG. Visual field loss was measured with automated threshold perimetry (either Octopus program 32 or Humphrey program 30-2). Optic nerve head cupping was classified as diffuse, focal, or mixed on the basis of stereo disk photographs. Diffuse cupping was defined as apparent concentric enlargement of the cup, with intact neural tissue for 360 deg. Focal cupping was defined as a disk which appeared relatively normal except for a partial or complete notch in the rim in either the superotermporal or inferotemporal position. Mixed cupping was defined as a combination of these and included

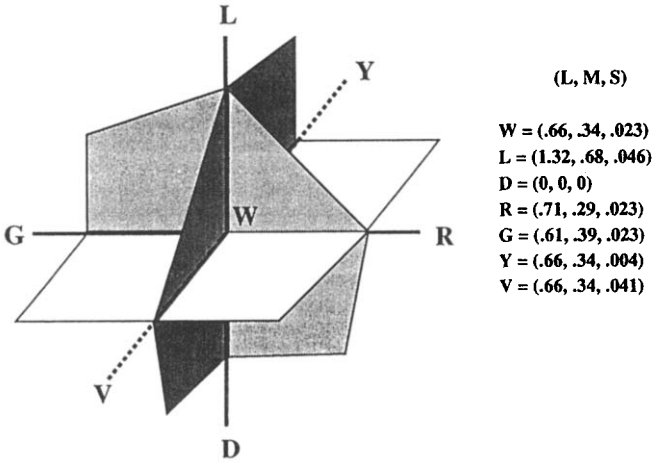

FIGURE 1. Three-dimensional cardinal color space. The RG/YV equiluminant plane is shown in white. The RG/LD plane is shown in light gray, and the YV/LD plane is dark gray. The boundaries of the planes indicate the range of colors possible with the equipment used. The maximum values attainable on the axes are given as (L, M, S) excitations in MacLeod–Boynton coordinates (MacLeod & Boynton, 1979). Mid-white (W) is at 50 cd/m^2. RG axis: L- and M-cone excitations change linearly in equal but opposite steps, (L + M) and S-cone excitations remain conatant. YV axis: S-cone excitations change linearly, L- and M-cone excitations remain constant. LD axis: S-cone excitations change proportionately from dark to light.

disks with sloping to the entire temporal rim. Pupil diameters ranged from 2 to 4 mm. Patients with pupil diameter less than 2 mm were excluded from the study. None of the patients had a history of systemic disease, and none of the eyes studied showed evidence of significant lens opacities. Patients were also excluded from the study if they had congenital red–green color vision defects. A diagnosis of congenital red–green color defects was based on history, and on the mid-matching point and range obtained on a Nagel-type anomaloscope.

The 25 observers who comprised the control group had no known abnormalities of the visual system, and normal color vision as tested by the Nagel-type anomaloscope and by the Farnsworth–Munsell 100-hue test.

All subjects gave informed consent to participate in this study; the research followed the tenets of the Declaration of Helsinki and was approved by the NYU Human Subjects Committee.

Chromatic and achromatic discrimination thresholds

Apparatus. Stimuli were presented on a Tektronix 690SR color television monitor; the screen was refreshed at 120 interlaced frames per sec. The 512 × 480 pixel display subtended 10.67 × 10.00 deg of visual angle. The mean luminance of the screen was 50 cd/m^2. The CIE (x, y) coordinates of the television phosphors were: red (0.63, 0.34), green (0.31, 0.595), and blue (0.155, 0.070). Images were generated by using an ADAGE 3000 raster-based frame buffer generator. The ADAGE provided 10-bit specification of the output of each gun leading to a palette of 2^{30} possible colors of which 256 could be displayed on any one frame. For a detailed description of the calibration procedure see Zaidi and Halevy (1993).

Stimuli. The range of lights used in this study is shown in Fig. 1 [adapted from Sachtler and Zaidi (1992)]. The lights are specified in a three-dimensional color space with axes corresponding to the cardinal directions of Krauskopf *et al.* (1982). The labels, Y, V, R, G, L, and D represent the approximate color appearance of the end points of the axes and are to be used solely as mnemonics. The axes are defined in terms of changes in cone excitations (L, M, S) in MacLeod–Boynton coordinates (MacLeod & Boynton, 1979), where L, M, and S refer to excitations of the long-, middle-, and short-wavelength sensitive cones respectively. The end-coordinates along the axes represent the limits of the stimuli that can be presented by our apparatus. The center of the space, W, represents an equal-energy achromatic light with a luminance of 50 cd/m^2. The YV axis is defined by changes in S-cone input; L- and M-cone excitations are kept constant. The RG axis is defined by changes in L- and M-cone excitations in equal but opposite steps keeping both their sum and the short-wavelength sensitive cone (S-cone) input constant. Along the LD axis all three cone inputs are varied simultaneously in equal proportion. At W, in Fig. 1, (L_W, M_W, S_W) is equal to (0.66, 0.34, 0.023). For each observer, the sensitivities of the two color-opponent systems were evaluated by measuring discrimination between W and lights along the YV or RG axes. Sensitivity to achromatic contrast was assessed by measuring discrimination between W and lights along the LD axis. We have assumed that thresholds along the RG, YV and LD axes isolate the responses of the corresponding color systems based on the following evidence. The results of habituating to different color axes in this space (Krauskopf *et al.*, 1982) are consistent with the existence of three classes of post-receptoral systems, where the response of the RG system is proportional to $[L - (L_W / M_W)M]$, the response of the YV system to $[S - S_W(L + M)]$ and the response of the luminance system to (L+M). In addition, in terms of chromatic properties, LGN parvoneurons fall into two discrete classes similar to the RG and YV systems (Derrington, Krauskopf & Lennie, 1984).

Procedure. One eye of each observer was tested, the other being occluded throughout the test. The observer was first adapted to a 10 deg steady white adapting field of 50 cd/m^2 for 120 sec. A small dark spot in the center of the field served as a fixation point. Discrimination thresholds were then obtained for a foveally fixated test

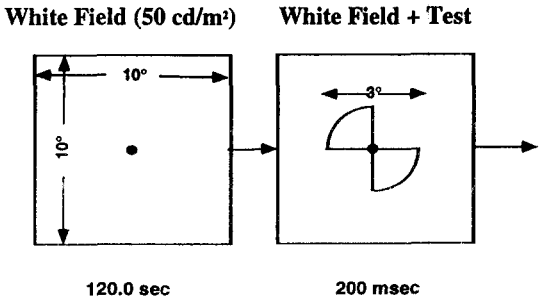

FIGURE 2. Spatial and temporal paradigm.

TABLE 2. Group mean threshold values and SDs along the three cardinal axes

	YV $\|\Delta S\|$		RG $\|\Delta L\| + \|\Delta M\|$		LD $\|\Delta L\| + \|\Delta M\| + \|\Delta S\|$	
Subject group	Mean	SD	Mean	SD	Mean	SD
Normal subjects ($N = 25$)	0.0015	0.0005	0.0041	0.0013	0.025	0.0053
Glaucoma suspects ($N = 13$)	0.0020*	0.0007	0.0055*	0.0016	0.029*	0.0057
Patients with OAG ($N = 27$)	0.0035†	0.0019	0.0085†	0.0049	0.043†	0.014

*$0.01 < P < 0.05$ (Mann–Whitney U test).
†$P < 0.001$ (Mann–Whitney U test).

light consisting of two quadrants of a 3 deg disk, 200 msec in duration (see Fig. 2). The observer's task was to indicate whether he or she could discriminate the test light from the background. Two random interleaved staircases tracked the 71% correct position on the psychometric function by increasing or decreasing the distance of the color of the test light from W along one of the cardinal axes. The final value of each threshold was the mean of eight transitions.

Equiluminance along the RG and YV axes was checked for each observer with flicker photometry at 22.5 Hz. Means and SDs were obtained for each observers' equiluminant settings. Observers with equiluminant settings that differed by more than 2 SDs from the equiluminant plane defined by CIE V_λ, were excluded from the study.

Results

The log discrimination threshold data were averaged for each group. The difference between the mean log threshold for the two groups of patients and the mean threshold for normal observers was calculated for each of the six directions along the cardinal axes. The differences in log discrimination thresholds for the two groups of patients are shown in Fig. 3. The mean threshold for normals is represented by 0.0. Compared with the control group, mean discrimination thresholds are increased for all cardinal directions for both groups of patients. Thresholds are increased more for the OAG group than for the glaucoma suspects. The mean threshold values for the three cardinal axes are summarized in Table 2. Thresholds are expressed as the difference in total cone excitation $|\Delta L| + |\Delta M| + |\Delta S|$ from W. Along the RG axis $|\Delta S| = 0$, and along the YV axis $|\Delta L| + |\Delta M| = 0$, therefore the units reduce to $|\Delta L| + |\Delta M|$ and to $|\Delta S|$ respectively. The increases in threshold in both groups of patients compared with the control group are statistically significant by both the t-test and the Mann–Whitney U (nonparametric) test. Threshold values for the glaucoma suspect group are intermediate between those for the normal control group and for the OAG group. The relative increases appear to be slightly greater along the two chromatic axes (YV and RG) than along the achromatic axis (LD).

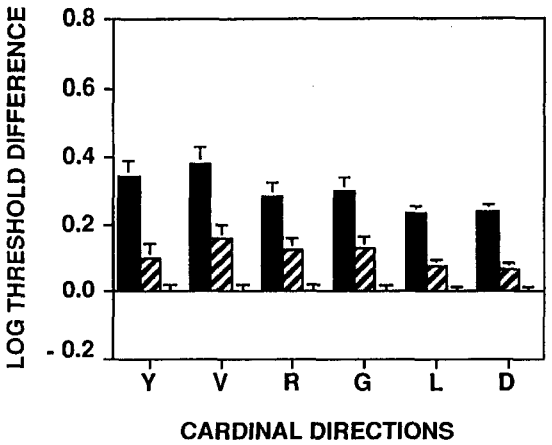

FIGURE 3. Mean threshold differences for the six cardinal directions for 27 patients with OAG (solid bars), and 13 patients diagnosed as glaucoma suspects (hatched bars). The error bars represent + 1 SEM.

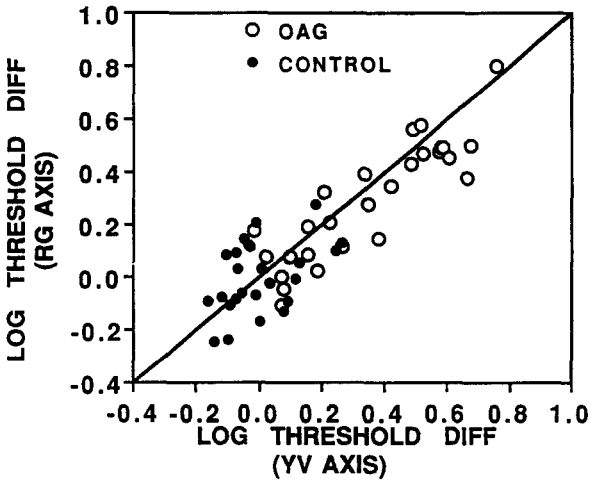

FIGURE 4. A comparison of log discrimination threshold differences along the YV axis to those along the RG axis. Each O represents the difference in log threshold for an individual patient with OAG from the control mean. The (0, 0) point represents the mean normal value. The ● represent differences in log threshold values for each normal observer compared to the mean log threshold value for normal observers. The diagonal line represents the locus of of equal threshold differences along the YV and RG axes.

We tried to investigate whether discrimination thresholds for the three cardinal axes are differentially affected by disease using analysis of variance. However our ability to interpret the results was limited by the presence of a positive correlation between the means and the variances of the log threshold values in the three groups of subjects, i.e. the higher the mean the larger the variance. A comparison of threshold differences determined for individual patients with OAG however, suggests that the disease has a similar effect on chromatic and achromatic discrimination thresholds. In Fig. 4, log

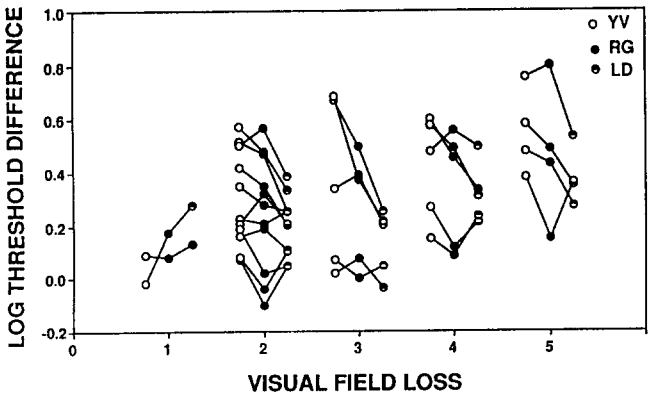

FIGURE 5. Threshold differences along the YV (○), RG (●) and LD (◒) axes as a function of the level of visual field loss for 27 patients with OAG.

discrimination threshold differences along the YV axis are compared to those along the RG axis. Each ○ represents the difference in log threshold for an individual patient with OAG from the control mean. The (0, 0) point represents the mean normal value. The ● represent differences in log threshold values for each normal observer compared to the mean log threshold value for normal observers. The diagonal line represents the locus of equal threshold differences along the RG and YV axes. Clearly, patients with increased thresholds along the RG axis have similar increases in threshold along the YV axis. Thresholds along the YV axis are correlated significantly with thresholds along the RG axis (Spearman $R = 0.87$). Similar results (not shown) were obtained for comparisons between the YV and LD axes ($R = 0.69$) and between the RG and LD axes ($R = 0.79$).

The effects of glaucoma at different stages of the disease process was assessed by comparing the increase in log threshold values for each OAG patient to their level of visual field loss. The classification scheme for the level of visual field loss is described in Table 1. Figure 5 shows the increase in log thresholds along the YV, RG, and LD axes for the 27 patients with OAG as a function of visual field loss. Using Spearman rank correlation coefficients we found the following correlations: for the YV axis ($R = 0.486$), the LD axis ($R = 0.441$), and the RG axis ($R = 0.351$). These positive correlations indicate that thresholds along all three axes increase with increasing severity of disease.

When we examined individual threshold values we found several examples of increases in threshold values along the YV and LD axes which were accompanied by minimal increases in threshold values along the RG axis. These data were obtained from patients with pigmentary glaucoma. Seven of the 27 patients in the OAG group had pigmentary glaucoma. The age range of this sub-group was 28–47 yr (mean age = 39.3 yr, SD = 6.6 yr). These patients were in a younger age group than the majority of patients and tended to have myopic refractive errors. We compared their threshold data to those of seven age-similar patients with POAG (selected patients are denoted by asterisks in Table 1). The age range of this sub-group was 29–50 yr (mean age = 41 yr, SD = 6.9 yr).These patients with POAG have similar refractive errors and similar visual field losses to the patients with pigmentary glaucoma. Rather than compare these two sub-groups of patients to the original group of normal observers who ranged in age from 24 to 70 yr, we compared them to the subset of 15 normals who were in a similar age range from 24 to 47 yr (mean age = 35.6 yr, SD = 8.2 yr). In Fig. 6 the log threshold differences for the three cardinal axes are plotted for seven patients with POAG [Fig. 6(A)] and for seven patients with pigmentary glaucoma [Fig. 6(B)]. Although the patients with POAG

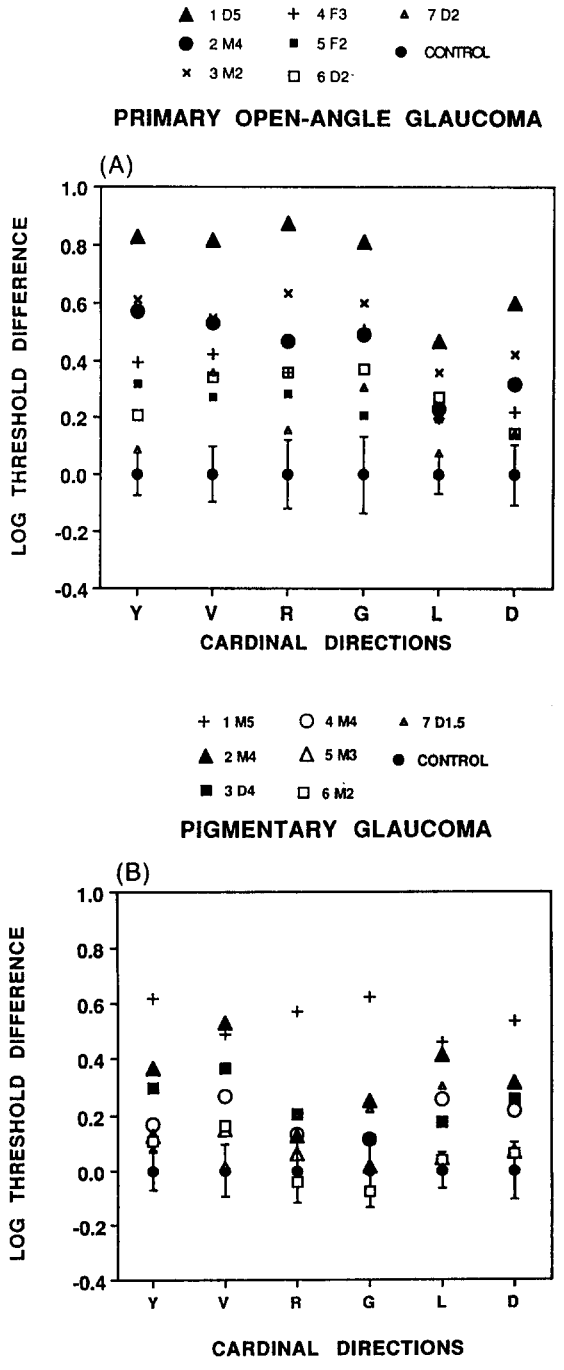

FIGURE 6. Threshold differences for the six cardinal directions for (A) seven patients with POAG and (B) for seven patients with pigmentary glaucoma.

TABLE 3. Clinical characteristics of patients—Expt 2

Subject	Age (yr)	Acuity	Visual field	Refractive error	Diagnosis
1	54	20/20−1	3	−5.00 + 1.00 × 11	PG
2	44	20/20	2	−1.50	PG
3	45	20/20−3	2	−5.25 + 1.25 × 85	PG
4	37	20/15−2	1	−1.25	PG
5	46	20/20−2	4	−1.50	PG
6	38	20/20	5	−4.75 + 2.0 × 105	PG
7	60	20/25−3	3	−8.00 + 1.25 × 90	PG
8	50	20/20−3	1	−6.00 + 1.00 × 90	PG
9	37	20/20	4	−3.25 + 1.50 × 90	POAG
10	44	20/25	3	−6.50	POAG
11	25	20/25	5	−5.25 + 1.50 × 95	POAG
12	47	20/20	2	−6.75 + 1.25 × 118	POAG
13	27	20/20	3	−6.00 + 0.75 × 100	POAG
14	36	20/20	2	−6.25 + 0.25 × 10	POAG
15	49	20/20	2	−10.50 + 1.00 × 100	POAG

POAG, primary open-angle glaucoma; PG, pigmentary glaucoma.

Visual field loss: 1, relative scotoma >6 deg from fixation in one hemifield; 2, relative scotoma in both superior and inferior hemifields; 3, arcuate scotoma in one hemifield, or scotoma ⩽6 deg from fixation, or absolute scotoma; 4, arcuate scotoma in one hemifield and relative scotoma in other hemifield; 5, arcuate scotoma in both superior and inferior hemifields.

show similar trends in threshold increases to those described for the OAG group (i.e. discrimination thresholds are increased for all cardinal directions), thresholds for patients with pigmentary glaucoma are increased by approximately the same amount along the YV and LD axes, and are accompanied by minimal increases along the RG axis.

EXPERIMENT 2

One of the interesting findings from Expt 1 concerns the possible difference between patients with pigmentary glaucoma vs those with POAG. The results shown in Fig. 6 imply that the deficits in the opponent and luminance systems are different for the two types of OAG. To investigate this further we ran 23 additional subjects using a criterion-free two-alternative forced-choice technique.

Methods

Observers. Twenty-three subjects participated in this experiment. The 15 patients were recruited from the glaucoma clinic at New York Eye and Ear Infirmary. Eight had pigmentary glaucoma (mean age = 47 yr, SD = 7.76 yr) and seven had POAG (mean age = 38 yr, SD = 9.42 yr). The mean age of the eight normals was 40 yr (SD = 9.7 yr). Table 3 summarizes the clinical characteristics and diagnoses of the patients.

Procedure. A two-alternative forced-choice procedure was used to measure chromatic and achromatic thresholds. The 2 deg, 200 msec test light consisted of two halves of a disk, one half at $W + 0.5T$ and the other at $W - 0.5T$, where T is the test amplitude along the predetermined color line. Foveal fixation was aided by a small cross. The division of the disk was randomly presented as either horizontal or vertical and the observer had to make a forced choice as to the orientation. A double random staircase was used to find the value of T at which the observer could discriminate between the two colors $W + 0.5T$ and $W - 0.5T$ with a probability of 0.71. Threshold was calculated as the mean of 12 transitions.

Results

The mean log discrimination thresholds for the two groups of patients and for the normal observers were calculated for each of the cardinal axes. The differences in log discrimination thresholds for the two groups of patients compared to the normal are shown in Fig. 7 where the mean threshold for normals is represented by 0.0. Discrimination thresholds are increased along the three cardinal axes for the patients with POAG. For patients with pigmentary glaucoma, increases in discrimination thresholds along the YV and LD axes are accompanied by minimal increases along the RG axis. The increases in threshold along the three axes in the group of patients with POAG compared with the control group are statistically significant by the Mann–Whitney

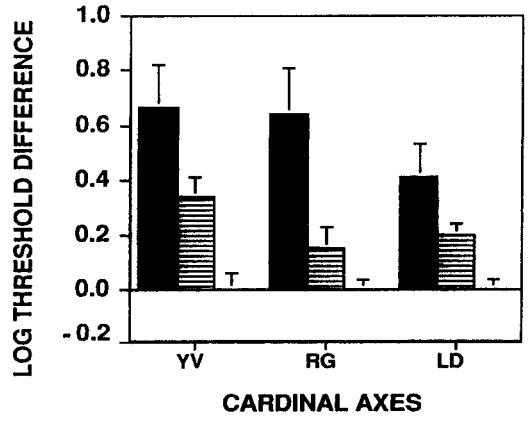

FIGURE 7. Mean threshold differences for the three cardinal axes for the group of patients with POAG (solid bars) and for the group with pigmentary glaucoma (hatched bars). The error bars represent + 1 SEM.

U (nonparametric) test (YV $P < 0.005$, RG $P < 0.002$ and LD $P < 0.02$), whereas for the patients with pigmentary glaucoma thresholds are increased significantly along the YV ($P < 0.005$) and LD ($P < 0.02$) axes but not along the RG axis. These results confirm the findings of Expt 1.

DISCUSSION

In this study of the effects of glaucoma on the sensitivities of the color-opponent and luminance systems, we found that patients with OAG and glaucoma suspects showed increases in chromatic and achromatic thresholds. Our results indicate that sensitivity losses, measured in the macular area, are not selective for the S-cone system in patients with OAG or for glaucoma suspects. For both groups of patients, sensitivity losses for the YV opponent system were accompanied by similar sensitivity losses for the RG opponent system and by decreased sensitivity to achromatic contrast.

The reduced sensitivity to short-wavelength light found in patients with glaucoma and in glaucoma suspects has been well documented, and the data have been interpreted as providing evidence that S-cone system sensitivity is selectively decreased by glaucoma. However, there are a number of studies of the effects of glaucoma on foveal color vision using spectral sensitivity techniques which have demonstrated that chromatic and achromatic sensitivities were reduced (Adams, Zisman & Cavender, 1982a; Adams *et al.*, 1982b; Zwas *et al.*, 1984), i.e. sensitivity losses were not restricted to the S-cone system. Our results are in general agreement with these studies, and with our preliminary study in which we compared measures of sensitivities of short- and middle-wavelength sensitive pathways to measures of chromatic and achromatic sensitivities obtained from eight patients with OAG (Greenstein *et al.*, 1993a, b). One difference between the results of the present study and our preliminary study is that we do not find evidence for preferential YV opponent system sensitivity losses in glaucoma suspects. Threshold values along the three axes for the glaucoma suspects are intermediate between those for the normals and those for the patients with OAG. Our results are also in agreement with the few studies which have used similar techniques to investigate the effects of glaucoma and increased intraocular pressure on color and luminance thresholds. For example, Kelly, Fourman and Petry (1993) measured foveal isoluminant color and luminance detection thresholds in patients with POAG and found that color and luminance thresholds were increased. Falcao-Reis, O'Sullivan, Spileers, Hogg and Arden (1991) assessed macular color contrast sensitivity in patients with glaucoma and reported that thresholds were increased along the three color confusion lines, protan, deutan and tritan lines, compared to thresholds for a control group or to thresholds for ocular hypertensive groups. Recently Felius *et al.* (1995) using a similar technique to ours also reported increases in thresholds of the blue–yellow, red–green, and luminance mechanisms.

Not only did we find that the sensitivities of the YV and RG opponent systems and the luminance system were reduced by OAG, but we also found that the pattern of sensitivity loss remained the same with increasing disease severity. With increasing severity of disease, sensitivity losses increased along the YV, RG and LD axes. We did, however, find a change in this pattern of sensitivity loss when we compared results obtained from a group of patients with pigmentary glaucoma to an age-similar group with POAG. For the patients with pigmentary glaucoma, a decrease in YV opponent system sensitivity was accompanied by a decrease in luminance system sensitivity, but the RG opponent system was minimally affected. The initial finding in Expt 1 was confirmed on a larger group of patients using a criterion-free forced-choice technique. What could account for the differences we have observed between these two groups? Pigmentary glaucoma is characterized by loss of pigment from the pigmented epithelium of the iris and the dispersion of pigment into the aqueous humor. Pigment deposits can be found on the central corneal endothelium, the surface of the iris, on the lens, zonules and within the trabecular meshwork. This type of glaucoma typically affects relatively young patients who have mild to moderate amounts of myopia. This is why we compared results obtained from patients with pigmentary glaucoma to those from a group of patients with POAG who were similar in age and had similar amounts of myopia. The results we obtained may reflect differences in duration and/or severity of the disease process or underlying differences in the causes of glaucomatous damage between the two groups. Glaucomatous damage is currently believed to consist of two broad types, diffuse and focal. It has been suggested that diffuse damage is induced by mechanical forces which induce diffuse axonal loss, concentric constriction of the visual fields, and enlargement of the optic cup. These patients have a more pressure-dependent disease, rarely develop disk hemorrhages, and are the ones who develop color vision deficits and pattern ERG abnormalities. Patients with focal damage tend to have lower IOPs and lower blood pressures. Disk hemorrhages are common and nerve fiber bundle and visual field defects correspond to arcuate bundle defects. Non IOP-induced mechanisms of damage are believed to be predominant, such as defects to optic nerve blood flow and/or autoregulation or other as yet unknown factors. Pure mechanical and pure "vascular" damage represent the extremes. It is likely that most patients with glaucoma have some degree of overlap—the higher the IOP at which the patient develops damage, the greater the mechanical effect. The lower the IOP at which the patient develops damage, the greater the vascular effect. It is possible that the patients with POAG in our study have a greater mechanical to vascular ratio underlying the development of glaucomatous damage than the patients with pigmentary glaucoma.

Can our results provide information about the possible underlying mechanisms of retinal damage? Based on the anatomical studies of chronic human glaucoma and experimentally induced chronic glaucoma in macaque monkey eyes, Quigley and his colleagues (Quigley,

Sanchez, Dunkelberger, L'Hernault & Baginski, 1987; Quigley, Dunkelberger & Green, 1988) have suggested that chronic elevated IOP leads to a selective loss of larger optic nerve fibers. These fibers are presumed to originate from retinal ganglion cells with larger somatic size. Since the larger retinal ganglion cells project to the magnocellular layers of the lateral geniculate and belong to the "M pathway", whereas the smaller cells project to the parvocellular layers, investigators have inferred that the M pathway is compromised more than the P pathway. Support for this comes from another study of the effects of chronic IOP elevation in macaque monkey eyes. In this study, Dandona, Hendrickson and Quigley (1991), reported finding a greater decrease in radioactive labeling of the magnocellular layers of the dorsal lateral geniculate nucleus than the parvocellular layers. However, in sections of the dorsal lateral geniculate nucleus which corresponded to the foveal region, they did not find any significant differential effects on the magnocellular and parvocellular layers. Recently Morgan (1994) in a critical review of the glaucoma literature, has questioned the suggestions that glaucoma results in selective cell loss. Do the results of our study imply that patients with OAG and glaucoma suspects have deficits in both M and P pathway processing?

It is well established that the large ganglion cells (M cells) have different functional characteristics from those of the smaller cells (P cells). In particular, Derrington *et al.* (1984) found that whereas P cells responded to chromatic differences, the M cells were relatively insensitive. The small amount of color opponency demonstrated in M cells by Smith, Lee, Pokorny, Martin and Valberg (1992) is unlikely to be a factor in the chromatic thresholds measured under our experimental conditions. In terms of the functional differences described above, the increase in chromatic thresholds we found for OAG patients and glaucoma suspects clearly shows that the P pathway is compromised, and that it is compromised during the early stages of the disease process. As the M pathway is known to have a higher contrast gain than the P pathway for achromatic contrast (Croner & Kaplan, 1995), it is tempting to conclude that the increase in thresholds along the LD axis shows that the M pathway is also compromised. Some caution is needed regarding this interpretation. Our achromatic stimulus was large enough to selectively favor detection by M cells (Croner & Kaplan, 1995), however the sharp boundary would also evoke responses from P cells. In addition if we assume the LD thresholds represent probability summation between the M and P pathways, then if only P pathway sensitivity was compromised this would also result in a smaller increase in LD thresholds than in chromatic thresholds.

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